Plant-Driven Design and Phytotechnology to improve the built environment

THE DESIGN AFTER

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PLANT-DRIVEN DESIGN AND PHYTOTECHNOLOGY TO IMPROVE THE BUILT ENVIRONMENT

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In post-industrial cities the quality of built environment is partially affected by the high concentration of chemical pollutants in outdoor and indoor spaces. An increasing number of people spend about 90% of their daily time in indoor environment that often has a higher concentration of pollutants than outdoors. The presence of many chemical compounds and the absence of natural elements contributes to reduce the healthiness of indoor spaces and to trigger the Syndrome of Sick Building in occupants. Many researches support that natural ecosystems have a positive effect on human health and other studies show the benefits provided by the application of phytotechnology. This paper discusses the opportunities offered by the application of plant-based solutions to improve the healthiness of built environment (especially the indoor air quality) and to re-establishing a relationship between man and rural spaces, with positive implication on psychological well-being. Phytotechnology includes many techniques to remediate polluted sites or to mitigate effects of anthropogenic activities using plant's metabolism according with technological solutions. In the paradigm shift toward an ecological view, natural ecosystems are considered as a part human society and plants are good indicators of the quality of the environment. This study focuses on the review of ecosystems services provided by plant-based solutions and it also reflects on the inclusion of phytotechnology in design practice for the well-being of people in indoor spaces and more in general in post-industrial cities.

Keywords: plant-driven innovation, nature and human health, healthiness of built environment, phytotechnology, design for sustainable living

INTRODUCTION

Technological developments have brought a substantive revolution in human society. For the first time in the human history, more than half of global population, approximately 55%, is living in urban areas (UN-Habitat,2011; Carli et al, 2015). Predictions regard the future of human society confirm this trend: the future will be characterized by urbanization (Randers, 2012). Global population is growing fast (United Nations, 2017) and all over the world people are moving from rural areas towards cities with the purpose to find safety and new opportunities for living. The UN-Habitat (2016) estimates that by 2050 about 70% of the population will live in metropolitan areas.

The increasing urbanization affects people's lifestyles and the political agenda that should focus on tackling problems related to the use and consumption of resources and the health of the urban environment. The rapid growth of cities causes environmental degradation, loss of biodiversity and ecosystem services (Harding, 2012). An important aspect of urbanization trend and virtual technology is that people are spending almost 80-90% of their daily time in indoor spaces such as school, home, workplaces and other public spaces (Liu et al., 2019). Outdoor and indoor air quality in the most of cities, with a population more than 1 million, fails to meet World Health Organization guidelines for healthy living (WHO, 2016). Moreover, the concentration of air pollutants in interiors is often higher than in outdoor spaces (Marchland at al., 2006).

In this scenario, the urgency is to undertake a paradigm shift toward an ecological perspective (Capra & Luisi, 2014) of built environment and also of interiors. Benefits provided by parks and green infrastructures in cities are widely discussed in many researches (Suzuki, 2015; Stigsdotter, 2015), while their effectiveness in indoor spaces is still an uncertain topic. This paper focuses on the opportunities provided by technological green, such living wall, to improve indoor air quality. Living walls are investigated as constructed ecosystems that integrate phytotechnology in interior design practice. The investigation underlines main strengths and problems in applying principles of *nature-centred approach* of phytotechnology in designing not only aesthetically, but also functional indoor green systems. Nature-centred design is a concept recently introduced by Van der Ryn (2013) and Tarazi et al. (2019), that supports the Human-centred design according to the urgencies expressed by the Anthropocene. It adopts a more holistic and ecological view to the design practice and it use design research tools to investigate complex problems.

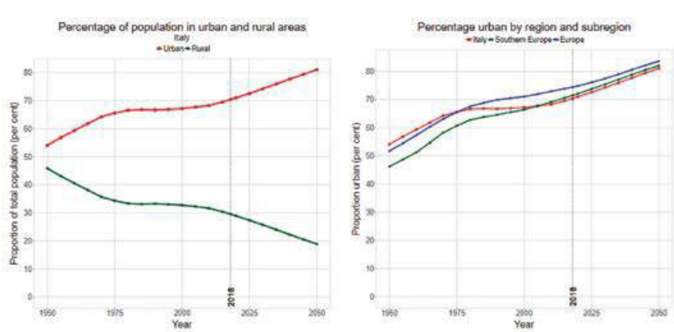

Figure 1. The first graph shows urban (red line) and rural (green line) population in Italy as a percentage of the total population, 1950 to 2050. The second graph shows proportion of urban population in Italy (red line) as compared to the Southern Europe (green line) and Europe (blue line). The proportion is expressed as a percentage of the total population, 1950 to 2050. Data from the United Nation DESA Urbanization Prospects (2018).

CHARACTERISTICS OF AIR QUALITY IN INDOOR SPACES AND CONSEQUENCES ON HUMAN HEALTH

In recent year, increasing attention has been focused to improve the *indoor environmental quality* (IEQ) and the comfort of interiors. The IEQ involves a huge set of parameters that includes light intensity, visual and acoustical aspects, thermal comfort and air quality (Bluyssen, 2009a). Indoor air quality (IAQ) is an important aspect of IEQ because it causes complications on human health and it has also consequences on occupant's performances (Ataroldi et al., 2018). IAQ is characterized by the concentration of specific compounds that cause indoor air pollution and it also depends by the features of buildings and by the habits of occupants. It can be distinguished in chemical and biological pollution based on the emission source. This investigation considers only chemical compounds that influences indoor air pollution and interaction of plants with them. Bluyssen (2009b) asserts that IAQ can be integrative approached from three perspective: indoor air of the space, sources that releases harmful compounds and human point of view. In addition to these, the outdoor air pollution has a serious influence on increasing the concentration of specific compounds in indoor air. Moreover, the aim to reduce the energy consumption for mechanical air ventilation systems encourages to investigate alternative solutions to improve IAQ and IEQ.

Indoor air perspective and sources of emission: regulations and recommendations

Indoor air is often expressed in terms of ventilation rate and concentration of specific compounds. The World Health Organization (WHO) (2009; 2010) selected a list of chemical compounds and defined general guidelines for their concentration limits and their effects on human health (Table 1). In addition to these, Ozone (O_3), Carbon dioxide (CO_2) from human metabolism, Particulate matter (PM_{10} and $PM_{2.5}$) from ambient pollution and Total Volatile Organic Compounds (TVOC) can affect indoor air quality. In many countries official regulation regards the presence of air chemical pollutants is still missing and general standards are not enough to meet the satisfaction of occupants (Ferrero, 2018). Many of these compounds can be registered in the most of indoor environment because they are released by furniture, paints, cleaning products, electronic device, building materials (Yangpen et al., 2018) and their concentration also depends by human activities, such as cooking. The evaluation of outgassing rate is a complex process because it depends by many factors such as the content of volatile compounds and solvents in the indoor air, and by the age and status of materials.

CHEMICAL COMPOUND	CONCENTRATION LIMITS	SOURCE OF EMISSION AND UTILIZATION	CANCEROUS FOR HUMANS
Benzene (C_6H_6)	6 x 10^{-6} µg/m^3 (UR/lifetime)	Paints, building materials, tobacco, heating and furniture	Group 1
Carbon monoxide (CO)	10 mg/m^3 (8 hours)	Combustion in O_2 deficit condition	-
Nitrogen dioxide (NO_2)	40 µg/m^3 (year)	Combustion	-
Formaldehyde (CH_2O)	0.1 mg/m3 (30 minutes)	Furniture in chipboard, household cleaning products, paints, heating and electronic components	Group 1
PAHs and $C_{20}H_{12}$	8.7 x 10^{-5} ng/m^3 (UR/lifetime)	Petroleum refining	Group 1
Trichloroethylene (TCE)	4.3 x 10^{-7} µg/m^3 (UR/lifetime)	Industrial solvent	Group 1

Table 1. List of some indoor air pollutants, their concentration limits (WHO, 2010), main sources of emission and levels of carcinogenicity for humans (WHO, IARC, 2018).

The issue concerns the release of harmful chemical compounds by adhesive in plywood, fiberboard and particleboard furniture and by many other household products, such as textiles, is very relevant in residential-typical conditions (Salthammer, 2019). For potential hazards on human health due to high concentrations of formaldehyde, many important furniture companies are moving toward the use of glue, adhesive, resins, painting and finishing without harmful chemical compound (IKEA, 2018). Synthetic filters of Heating, Ventilation and Air Conditioning systems can also release formaldehyde at the room temperature of 20°C and 80% of relative humidity.

Human health implications

Human perspective regards IAQ reflects the effect on health and wellbeing of exposure to chemical pollutants in indoor air. In comparison to the great importance that ambient (outdoor) air pollution in urban areas has reached in last decades, IAQ does not have the same relevance in political and environmental agendas. Even though, the WHO (2018) established that 3.8 million people a year die prematurely because of exposure to harmful compounds in indoor environments. High concentrations of chemical pollutants and of VOCs contribute to causing the *Sick Building Syndrome* (SBS) and the *Multiple Chemical Sensitivity Syndrome* in occupants. They occur with a set of health problems, firstly respiratory problems, that affect working and learning performances especially in young people and children (Kishi et al., 2018).

PHYTOTECHNOLOGY: FROM ENVIRONMENTAL APPLICATIONS TO INTERIOR OPPORTUNITIES

Concerning environmental issues, the concept of phytotechnology means a huge set of techniques and applications that use plant for providing non-invasive solutions, including phytoremediation and bioremediation processes. It is the use of vegetation to remediate, contain or prevent contaminants, and add nutrients, porosity and organic matter (Kennen & Kirkwood, 2015). Phytotechnology is based on ecological principles and living systems mechanism and it is included in *ecotechnology* techniques (Aida, 1995). It is an interdisciplinary field of study that involves discipline as engineering, planning, design and botany to implement on-site solutions. Phytotechnology applications are successfully tested on soil, groundwater and wastewater management, while in the treatment of air, especially for indoor applications, development of phytotechnologies to remove airborne pollutants is just beginning (Henry et al., 2013).

It is necessary to make a distinction between the term *phytoremediation* and *phytotechnology*. The first concept describes the degradation and/or removal of a contaminant from a polluted site by a specific plant or group of plants. While phytotechnology also includes all plant-based solutions, such as green walls,

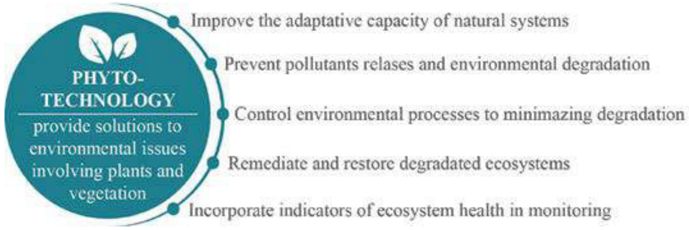

Figure 2. Main phytotechnology application.

green roofs, bioswales and constructed wetlands, to remediate or mitigate an ecological problem (Kennen & Kirkwood, 2015). Phytotechnology can be described as nature-centred approach to manage environmental issues which considers living systems as fundamental part of human society, including cultural aspects, and public health.

Phytotechnology uses opportunities provided by plants' mechanisms contributing in remediating contaminants from soil, water and air medium. Generally, the use of plants in contrasting effects of pollutants involves more than one of following physiological processes (Table 2) that are complementary for the entire phytoremediation. In case of low levels of contaminants concentration, these mechanisms are spontaneously used by vegetation in the process of *natural attenuation*.

Table 2. Plants' mechanisms and their principal applications in the treatment of soil, water and air.

NAME OF PLANT MECHANISM	ORGANIC/INORGANIC CONTAMINANTS	MECHANISM DESCRIPTION	APPLICATION
Phytodegradation	Organic	Plant uptakes contaminants and breaks into non-toxic metabolites	Soil, Water, Air
Rhizodegradation (plant assisted bioremediation/ degradation)	Organic	Roots exudates and/or the soil microbiology in the root zone break down contaminants	Soil, Water, Air
Phytovolatilization	Organic/Inorganic	Plant uptakes pollutants and release them into the atmosphere as gas	Soil, Water, Air
Phytometabolism (or phytotransformation)	Organic/Inorganic	Inorganic elements (as N, P, K) and organic metabolites produced by phytodegradation are metabolized and incorporated in plant's biomass	Soil, Water, Air
Phytoextraction	Organic/Inorganic	Plant uptakes pollutants and move them into plant parts. For organics, it is coupled to phytodegradation process	Soil, Water, Air
Phytohydraulics	Organic/Inorganic	Plant's roots ability to stop migrating plumes	Water
Phytostabilization (or phytosequestration/ phytoaccumulation)	Organic/Inorganic	Plant holds contaminants in place, and it does not move off site. Contaminants are made less bioavailable.	Soil, Air, Water
Rhizofiltration	Organic/Inorganic	Roots filter out pollutant from water	Water & Soil

In the application of phytotechnology for the treatment of air contaminant, plants take advantage of the characteristic of being a *colony* for microbes. Phyllosphere (Wei et al., 2017; Bringel & Couée, 2015) and rhizosphere (Dela Cruz et al., 2014; Moya et al., 2018), plant's leaves (cuticle and stomata) and roots structure and their associated microbiota, cover an important role in the interaction with chemical compounds (Agarwal, 2019). Phytotechnology air for organic pollutants treatment provides great opportunities in terms of *field applications* and *relative remediation time* (Kennen & Kirkwood, 2015).

General overview on laboratory and field testing of indoor air phytoremediation ability

The attention paid to the capacity of plants to uptake and degrade contaminants from indoor air raised in the 1980s with pioneer studies succesfully conducted by NASA on benzene, formaldehyde and trichloroethylene (Wolverton et al., 1989). Afterwards, many other studies were conducted to test in laboratory potted plants' phytoremediation ability and their efficiency (Righetto, 2018; Yang et al., 2009). Based on studies of Wolverton et al. regard plants selection, many species of plants were tested and compared in controlled and sealed chamber experiments. In this condition, parameters such as duration of testing, light intensity, humidity, temperature and concentration of the contaminants are strictly controlled and monitored, unlike what happens in real context. Plants degrade chemical compounds through respiration and photosynthesis by leaf surface absorption and relevant results were also obtained analysing rhizosphere (plant's roots and microorganisms) phytoremediation ability. Significant results are achieved in the phytoremediation of indoor airborne particulates, PM_{10} in particular, (Pegas et al., 2012; Soreanu et al., 2013); of VOCs (Dela Cruz et al., 2014), and of NO_2 and CO.

In on-site testing, the main problems regard the great variability of above parameters in real context conditions. The efficiency of plant-based applications depends by indoor environmental features, also regard the number of occupants and their habits, by the plant's specie, by total plant's leaf area and by plant's physiology in relation to the condition of surrounding environment. Moreover, limited spaces available in interiors is a main driver that limits an effective application of plants with air remediation purpose. In recent investigations (Pérez-Urrestarazu et al., 2016; Tudiwer & Korjenic, 2017; Abdo et al., 2019) indoor vertical green systems are tested with the purpose to evaluate their performance in improving IAQ and IEQ, especially regard CO_2 sequestration and regulation of relative humidity and temperature. Green wall system is a consolidated technology for outdoor application, but its benefits as functional

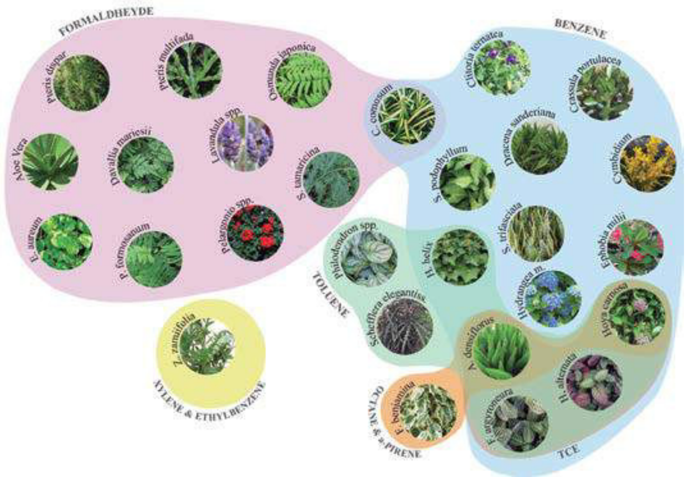

Figure 3. List of most tested ornamental plants for indoor environment (Agarwal et al., 2019).

green technology for indoor environment are almost unknown. Vertical green system (also known as living wall system) is a valid solution to increase the number of plants and the total leaf area in indoor spaces. Many studies (Pérez-Urrestarazu et al., 2016; Moya et al., 2018; Petit et al., 2018; Abdo et al., 2019) are testing the performances of active living wall systems (biofilter green wall systems) to investigate air bioremediation ability of plant's rhizosphere (especially regard VOCs treatment).

Functional living wall systems, not only aesthetically, can be interesting applied in public and shared spaces, such as schools, offices and co-working spaces. Positive effects on occupant's education, awareness, comfort satisfaction, psychological wellbeing, working productivity and learning skills of indoor greenery practice are well documented, while indications to improve IAQ are still uncertain, especially for traditional living wall systems. However, studies conducted on indoor phytoremediation published lists of plant species that have achieved good performances (Figure 3). The most of ornamental plant species analysed are shade-loving and with rich foliage (green leafy part) that produce less pollen and bloom to avoid the risk of allergic or negative response in occupants.

Opportunities and constrains in applying phytotechnology to real context

Complexity in the nature and sources of air pollutants and of other environmental features requires that plant-based solutions are site-specific design processes. There is not a unique definition of a clear methodology for designing living wall systems that is valid for all indoor environment: plant species, substrate of cultivation, microbe and structure that support the entire

OPPORTUNITIES

- **Natural, passive, solar energy-driven and methods to regenerate and clean up built environment**
- **Non-invasive solution and adaptable for specific site**
- **Possible application for treating a wide range of contaminants**
- **Multidisciplinar approach that combine chemistry, physic and biology with design and technical disciplines**
- **Well-accepted technologies for aesthetical and visual value**
- **Pollution prevention and mitigation effect**
- **Plant species for monitoring and assessing the ecosystem health**

SECONDARY OPPORTUNITIES

Community use: **involvement of stakeholders and people in planning stages**
Educational use: **classroom and living-lab experiences for increasing awareness and knowledge of plant world**

CONSTRAINTS

- **Some contaminants cannot be remediated by phytotechnologies**
- **Contaminant's level is too high for plant-base solutions application**
- **The elongated timescale to be effective (especially in soil and water)**
- **Fluctuation and vulnerability of natural systems (reactions to environmental and climate conditions)**
- **Context-based application: it depends by the characteristics of that specific site**
- **Some application are quite expensive to be really effective and to maintain them (range cost for 1m² of green wall: 250 - 600 euro)**
- **Boundaries of systems are not well defined, especially in case of atmosphere (outdoor air) in urban areas**

Figure 4. Opportunities and constrains in the application of phytotechnologies for the treatment of chemical compounds and positive implications at the community level.

living wall should be quite different for each environment. The selection of plant and design method occurs after a specific characterization of the context and of users/occupants. This step is particularly relevant to identify users' needs, their habits and expectations regards the usability and interactions level with the vertical green system. Needs expressed in school environments are different from co-working spaces, private offices and healthcare buildings: some technical measures are essential in specific context to maintain the safety of users. The application of phytotechnology mechanism in indoor environment through the design of living wall systems presents interesting opportunities but constrains are also prominent (Figure 4). For example, costs for the entire life cycle of living walls, including costs for maintenance, could affect decision making especially in public buildings (e.g. schools). Some companies, such as Terapia Urbana (Sevilla, Spain), Naava (Helsinki, Finland) and Junglefy (Banksmeadow, Australia), offer design solutions and products to build aesthetically efficient living walls applying different technologies. The ongoing and future challenges investigate ways and technologies to increase the effectiveness of indoor living walls for the improvement of air quality and indoor environment. It is possible by investigating plant configurations, cultivation substrates and low energy solutions to improve the phytoremediation ability of indoor living walls and to reduce costs for operations, installation and maintenance. Living wall technology is an open research field investigated in collaboration with research groups and universities.

DESIGN WITHIN LIVING SYSTEMS: TOWARDS AN INTEGRATIVE APPROACH IN DESIGN PRACTICE

The increasing attention on sustainability requires a paradigm change in design practice towards an ecoculture thinking that focuses on designing living spaces looking at nature as a model (Benyus, 1998). In recent year, the cross-disciplinary approach of *Biodesign*, the practice of design with biology, ecology and engineering, and the *Biophilic Design* (Kellert et al., 2008, Sanchez et al., 2018, Xue at al. 2019, Abdelaal, 2019) that improves health and well-being in built environment have become relevant in the panorama of design. Biodesign goes beyond *biomimicry* and it refers specifically to the involvement of living organisms and their principles as an essential component for functioning (Myers, 2018). Phytotechnology can be defined as a nature-centred approach that consider plants as partners in improving build environment and containing or remediating harmful impacts caused by human activities. Opportunities provided by plants for the improvement of IAQ should be involved in the practice of biophilic design supported by technical and scientific knowledge. The nature-centred design strategy must consider also to sustain and support plants' life in unusual indoor context for growing, far from natural environment. This aspect and the necessity of reducing the energy for lighting and for mechanical air ventilation, often used in biofilter green walls, are main challenges in phyto-design for improving the IAQ. In order to achieve good air phytoremediation performance, plants must be in good health and design must support and promote flourishing growth providing proper technical equipment. Living wall systems can be described as constructed ecosystem, integrated in urban environment, which must support plant.

CONCLUSIONS

The urgency to improve the environmental quality and sustainability in urban areas encourage to take into consideration natural systems and their properties. The main challenge is to define technical and ecological indications for including nature ecosystems in the design of built environment towards a *regenerative* approach. Humans depend completely from the presence of plants on the Earth's surface for food, soil regeneration, provision of oxygen and more in general for the mitigation of climate conditions. Plants are essential for human life and they should be considered as strong partners in development processes. It requires to move from an anthropocentric view of life towards a systemic perspective and a long term attitude understanding the important role of living systems in restorative design practice. In many cases, they have already solved issues to improve resources efficiency and their regenerative ability (Mancuso & Viola, 2015; Bruni, 2015). Taking into consideration the strong increase in urban population, plants are essential partners to reestablish the important relationship between humans and natural environment in metropolitan areas.

Plant-driven design and nature-centred design that includes phytotechnology's opportunities show interesting way to improve the quality of built environment. As dynamic systems and living organisms, plants interacts with the surrounding and intelligently responds to its stimulations, adapting themselves to the context. Although plants are among the oldest organisms in the world, they remain largely unknown. For an effective and functional application of plants' intelligence and of their living mechanism in indoor spaces, phyto-design practice should promote the transfer of knowledge between disciplines to define the best site-specific solutions.

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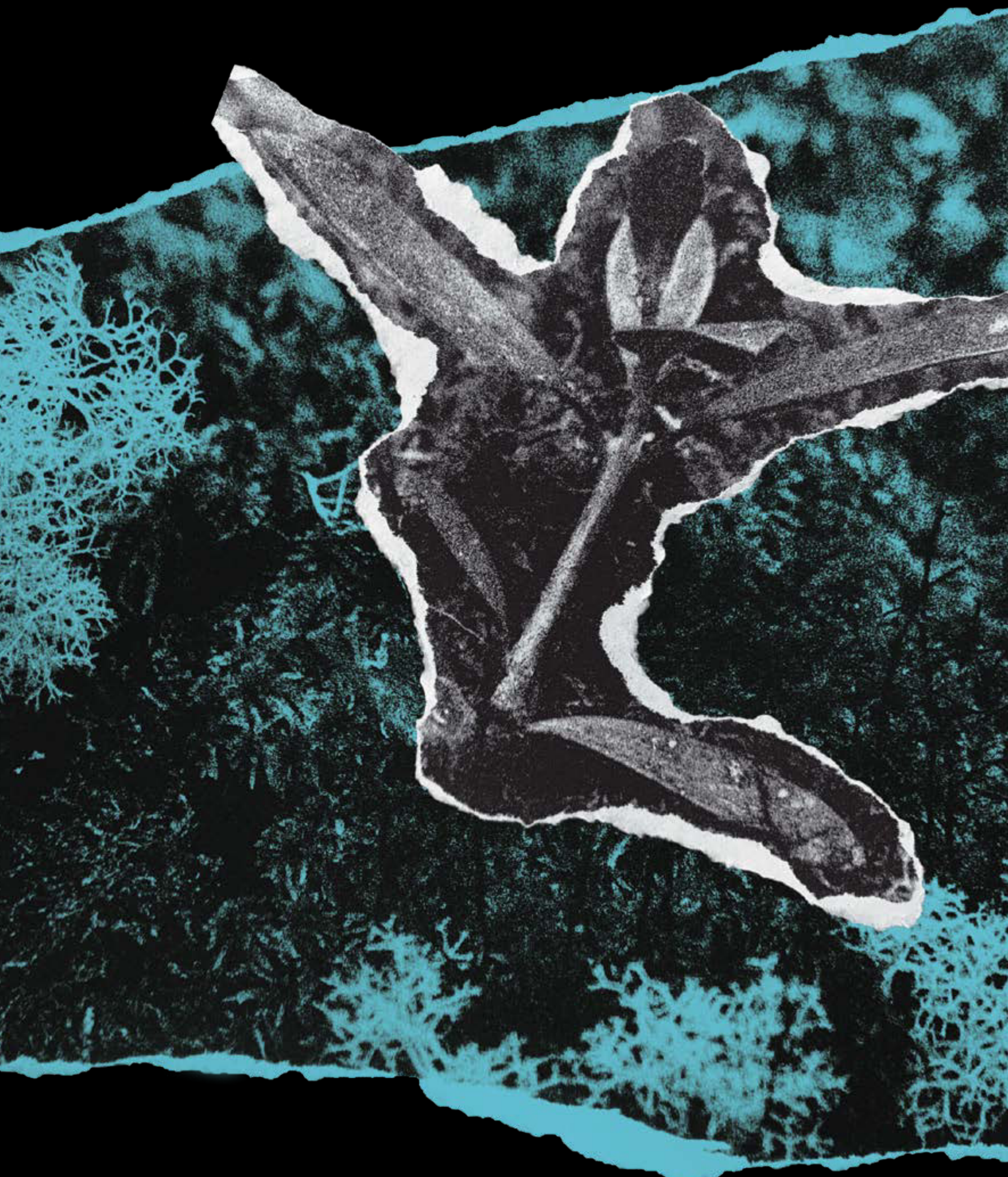

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